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USING FORWARD-FOLDING OF SERTS AND *YOHKOH* SXT DATA TO ESTIMATE THE ELECTRON DENSITIES OF CORONAL PLASMA

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Introduction

Understanding features and phenomena on the Sun requires knowledge of the basic plasma parameters, such as composition, temperature, emission measure, electron density, filling factors, and their distributions. Establishing the distribution of emission measure (the amount of emitting material) with temperature is the first step needed to proceed with most of the interesting physics of active regions -- including heating processes, cooling timescales, and loop stability. The reliability of emission measure distributions derived from spectroscopic observations usually depends upon the validity of the assumptions about the absolute elemental abundances, ionization fractions of the emitting ions, and the electron density. Inaccuracies in the electron density assumptions can lead to emission measure distributions that do not correctly describe the observed plasma.

To determine the electron density of the emitting plasma, we first modeled the temperature distribution of NOAA Active Region 7563. We have combined broad-band filter data from the Yohkoh Soft X-ray Telescope (SXT) with simultaneous spectral line data from the Goddard Solar EUV Rocket Telescope and Spectrograph (SERTS) taken during its flight on 1993 August 17.

We have used a forward-folding technique to determine an emission measure distribution of the active region loops using different assumptions for the electron density while holding other assumptions about the plasma constant. Elemental abundance uncertainties were not a major factor here because we chose to work only with iron lines and the SXT responses are dominated by iron lines.

We used densities of 5×10^8, 10^9, 5×10^9, 10^{10} and 5×10^{10} cm^{-3}. We have found that: (1) Assuming an electron density of 5×10^9 cm^{-3} yields a good degree of agreement between theoretical and observed results. (2) With an electron density significantly higher or lower than this value, it becomes increasingly difficult to derive an emission measure distribution with good agreement between theoretical and observed results. The results of our multithermal analysis imply that an average electron density of 5×10^9 cm^{-3} is a satisfactory assumption for the plasma of AR 7563 as viewed by the SXT and the SERTS instruments.

Observations

AR 7563 was observed simultaneously by SERTS (Neupert et al. 1992) and SXT (Tsuneta et al. 1991) on 1993 August 17. The analysis presented here is limited to a 2.7 arcmin (37 SERTS pixels) by 4.4 arcsec (1 SERTS pixel) slice through the central portion of the active region. SERTS acquired spectrographic data between 235 and 450 A for about seven minutes during the rocket flight. Yohkoh SXT images of the target active region were obtained in three filters (thin Al, AlMgMn, and thick Al) with a pixel size of 2.455 arcsec. Images were taken before, during, and after the flight to check for episodic heating and structural changes. No significant changes were observed during the period of the SERTS observations.

Analysis

The density is a fundamental parameter of any coronal plasma and is essential when trying to understand the fundamental physics of complex phenomena such as coronal heating and loop dynamics. Plasma densities are usually determined from the ratio of intensities of two spectral lines, ideally from the same element and ionization state to avoid having to know the elemental abundances and the ionization fractions. The density sensitivity of these ratios arises because, for some classically forbidden transitions, the radiative decay rate is so small that the electron collisions compete as a depopulating mechanism and the population of the emitting level can become comparable to the ground level (Mason 1988). Brosius et al. (1996) used this method to calculate the electron densities from several pairs of iron lines observed by the SERTS instrument for the core of AR 7563. Their results are listed in the table below:

Ion	Line Ratio	Log Density
Fe XV	321.8/417.3	9.41 ± 0.22
Fe XIV	353.9/334.2	9.58 ± 0.14
Fe XIII	320.8/348.2	9.17 ± 0.09
Fe XIII	359.7/348.2	9.26 ± 0.10
Fe XIII	359.7/359.8	9.44 ± 0.13
Fe XIII	318.1/320.8	10.14 ± 0.20
Fe XIII	318.1/321.5	10.07 ± 0.20
Fe XIII	318.1/312.2	9.68 ± 0.18
Fe XIII	318.1/348.2	9.36 ± 0.09
Fe XII	338.3/352.1	10.30 ± 0.12
Fe XI	308.5/369.2	9.34 ± 0.43

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These results show a variety of densities ranging from 1.5 $\times 10^9$ to 2.0 $\times 10^{10}$ cm^{-3}, about an order of magnitude. Therefore, the results we found with the multithermal analysis were unexpected.

Forward folding is a standard technique used to determine a plasma emission measure distribution as a function of temperature. It requires an initial input model (a flat distribution was used here) which is folded through the spectral line emissivity functions or broadband responses. This produces a set of predicted intensities which are compared with the observed values. The emission measure distribution is then adjusted iteratively (and subjectively) to improve the agreement between the observed and predicted intensities while keeping the curve as smooth a function of temperature as possible. The process is repeated until, ideally, the predicted and observed intensities agree to within approximately 1-2 sigma of the observed values. The method is described in detail in the paper by Schmelz et al. (1999) who found that:

(1) the SXT response functions were sensitive to both the elemental abundances and the ionization fractions assumed to compute the solar spectrum that is folded through the instrument effective area;
(2) the relative calibration between the SERTS and the SXT instruments had to be adjusted by a factor of two (a value consistent with the absolute measurement uncertainty of the 1993 SERTS flight) no matter which abundances or iron ionization fractions were used;
(3) the two-peaked differential emission measure previously determined using SERTS data alone was not consistent with the SXT data -- including the SXT data as a high-temperature constraint in the analysis required that the emission above about 3 MK drop off steeply rather than extending out to 6 MK.

The intensities and uncertainties of the SERTS iron lines used in this analysis were published by Brosius et al. (1996) and the emissivity functions were computed using information in the CHIANTI atomic physics data base compiled by Dere et al. (1997). Figure 1 shows the column emission measure distribution that minimizes the difference between the predicted and observed intensities. The hybrid abundances of Fludra and Schmelz (1999) and the ion fractions of Arnaud & Raymond (1992) were used to compute this curve. (The shape of the curve changes somewhat if the ion fractions of Arnaud & Rothenflug 1985 are used, but the data are not good enough to determine which gives the better result.) The analysis also assumes a cross-calibration factor of two between SERTS and SXT, a value which is consistent with the absolute uncertainties of each instrument. See Schmelz et al. (1999) for the details of this analysis.

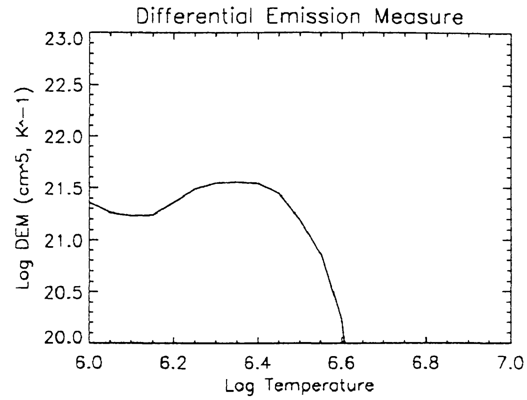

Figure 1. Column emission measure derived for Active Region 7563 using forward folding.

The emission measure curve in Figure 1 was originally computed assuming a density of 10^{10} cm^{-3}. This curve was chosen to optimize the fit of the intensities recorded in the three SXT channels since this instrument has the more reliable high temperature response. As a result the predicted intensities for the two Fe XVII SERTS lines are much lower than their observed counterparts. These lines have been problematic in other analyses. The discrepancies between observation and theory cannot be explained by any known or suspected problems with the data and it has been suggested that the atomic parameters for these lines be investigated in more detail.

The plots in Figure 2 show the predicted/observed intensity ratios for each of the SERTS iron lines as well as for the SXT filters for different values of the plasma electron density. Lines where the intensity increases as density decreases are shown as stars, and those where the intensity decreases as the density decreases are shown as squares. In the top plot ($n_e = 5 \times 10^{10}$ cm^{-3}), the squares are too high and the stars are too low; the reverse is true the bottom plot ($n_e = 5 \times 10^8$ cm^{-3}). The middle plot ($n_e = 5 \times 10^9$ cm^{-3}) gives the best results. It appears that the emitting loops of the stable active region under study have a mean electron density close to this value over a fairly large range in temperature.

The Gaussian distribution plots (Figure 3) show that there are errors in the data in addition to the statistical measurement uncertainties. The Fe XVII line intensities (points 30 and 31) may contain contributions from unresolved lines and the atomic physics for the Fe XIV lines (points 20-23) has recently been updated. We will investigate these lines in more detail as we continue our analysis.

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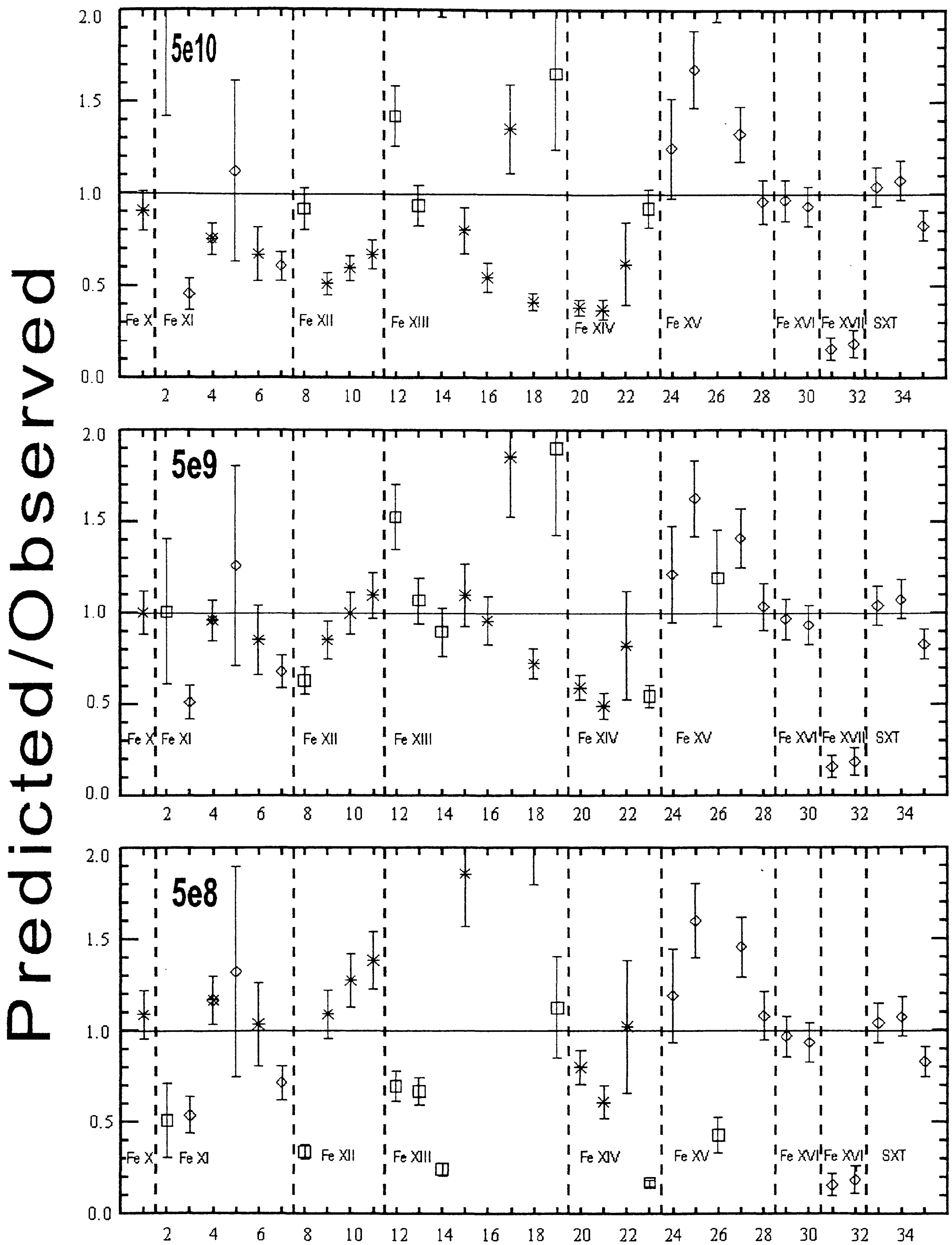

Figure 2. Error analysis plots showing the ratio of predicted to observed intensities using different values for the electron density. Points 1 to 32 show the values for the SERTS iron lines and points 33 to 35 show the values for the three SXT analysis filters.

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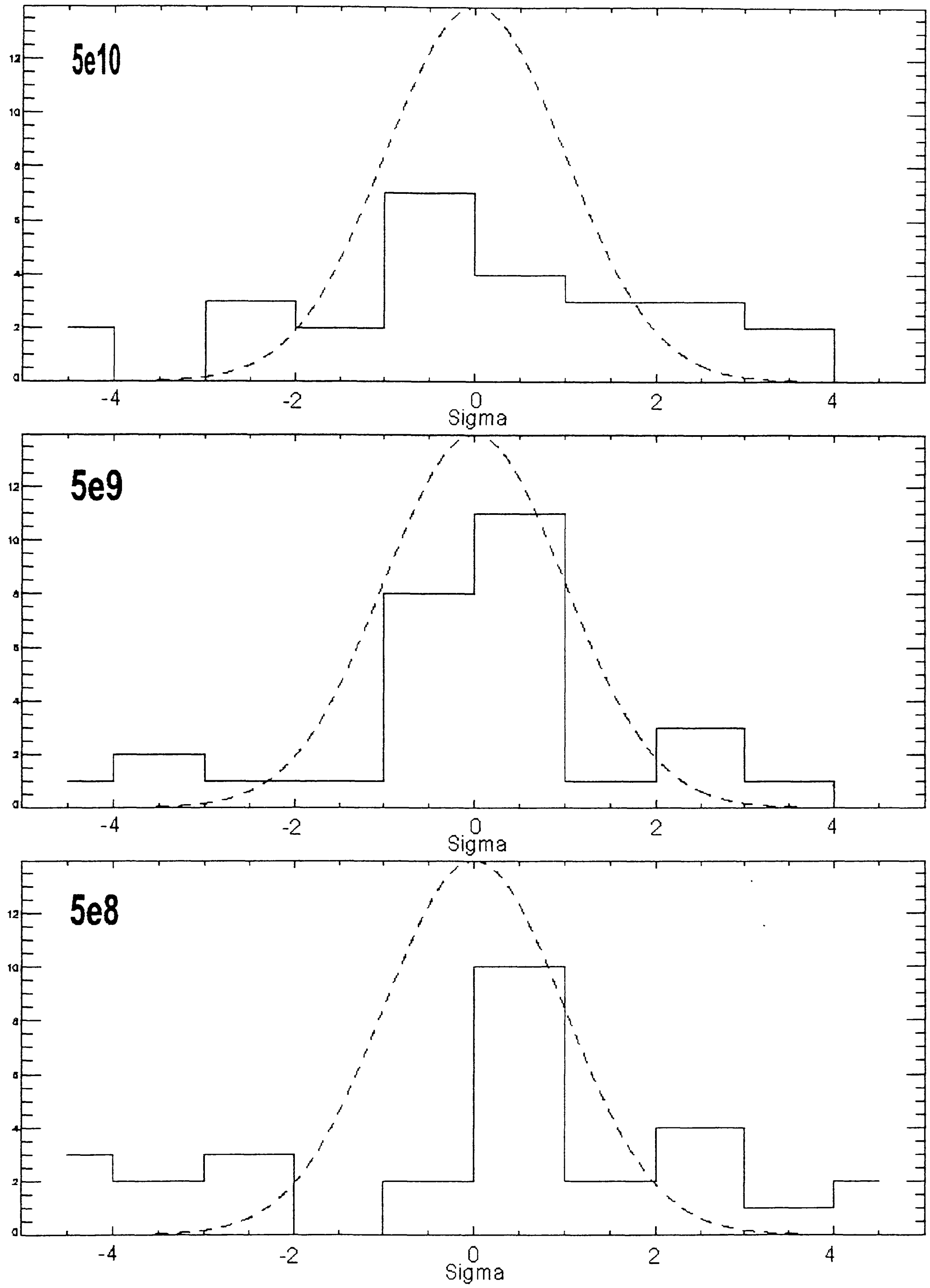

Figure 3. Gaussian distribution plots for the error analyses using electron densities of 5E10 cm^{-3}, 5E9 cm^{-3}, 5E8 cm^{-3}. The middle plot shows the best results, but it is clear from this analysis that instrumental uncertainties are not the only source of errors.

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Conclusions

This method of determining density is complementary to standard line-ratio density diagnostics. Because it uses a large number of spectral lines simultaneously, it is not weighted heavily by the potential atomic data uncertainties inherent in any given line ratio.

There is no a priori reason to think that all EUV/X-ray emission in the core of a given quiescent active region would come from loops with a single mean electron density. Our results lead us to postulate that, at least for stable, quiescent regions, there might in fact be a narrow range of characteristic mean densities over a broad temperature regime. We suggest that this forward-folding technique might be a powerful new density diagnostic tool.

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